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NAVAL AIR WARFARE CENTER AIRCRAFT DIVISION
PATUXENT RIVER, MARYLAND

TECHNICAL REPORT

REPORT NO: NAWCADPAX/TR-2004/19

AIRCRAFT CARRIER EXPOSURE TESTING OF AIRCRAFT MATERIALS

by

Dr. Eui W. Lee
N. Abourialy
J. Kozol, Navmar Applied Sciences Corporation

9 January 2004

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14. ABSTRACT Previous studies have demonstrated that the aircraft carrier environment in the western Pacific Ocean is far more severe than other marine or industrial environments. Laboratory accelerated tests do not necessarily reproduce the real time corrosion behavior of materials on board an aircraft carrier on deployment. Test and control specimens were affixed on exposure racks and installed on aircraft carriers to compare adhesive bonding primers for aluminum and to determine the static property behavior of various aluminum alloys after shipboard exposure. Laboratory accelerated sulfur dioxide salt spray tests were conducted on three of the same aluminum alloys. After multiple deployments, significant reductions in ductility occurred for some aluminum alloys while slight changes occurred in static strength values. Peak aged 7075-T6 aluminum sustained as much as 87% reduction in ductility and overaged 7075-T7 sustained a 45% reduction in ductility.			
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INTRODUCTION

A variety of materials and finishes are exposed in the Naval operating environment of aircraft carrier decks to determine their real time corrosion resistance and to screen the behavior of metals and alloys, composites, paints, corrosion protective coatings and adhesives used in the construction of Naval aircraft. The environment of an aircraft carrier deployed in the Western Pacific and the Indian Ocean, with a combination of high heat and humidity, salt content from water vapor and sea water, jet engine exhaust products and periodic monsoon rains creates severely corrosive conditions. Extensive exfoliation corrosion of unprotected high strength aluminum alloys can occur during much shorter periods of exposure than is observed in other seacoast or industrial locations [1]. Exfoliation of aluminum alloys in the T6 (peak aged) condition has been observed in specimens exposed aboard nuclear powered carriers (no stack exhaust gases) as well as conventionally powered carriers (stack exhaust gases) [2]. It appears that climate, along with the acidity of moist films due to jet engine exhaust leads to this extremely corrosive environment. Shipboard exposure testing is a reliable predictor of how materials and material systems will perform under Naval aircraft operating conditions and provides real time data to supplement laboratory accelerated tests.

SHIPBOARD EXPOSURE TESTING PROCEDURE

The exposure test rack frame consists of welded steel which is cadmium plated, chromate conversion coated, and painted with epoxy primer and polyurethane topcoat. The rack face is stainless steel mesh. Specimens are insulated from the rack face with nylon washers and fastened securely with nylon bolts and nuts. Silicone rubber sealant is applied to the fasteners to prevent crevice corrosion. It is necessary to ensure that specimens are fastened securely to the rack, as separation could lead to foreign object damage, a hazard for the aircraft. Specimens are exposed at a 45-deg angle to the vertical, as shown in figure 1. The test racks are spot welded to a structure on the ship where they can be exposed to climatic conditions, as well as to jet engine exhaust. Exposure test specimens are removed from the ship for examination and testing upon completion of deployment. For static mechanical tests, from 3 to 10 flat tensile specimens are exposed in each group and tests are conducted in accordance with ASTM Standard E8 [3]. For multiple deployment exposures, it is often necessary to remove the test racks from one ship and install them on another ship. No observations are made while the ship is on deployment, so as not to interfere with operations on board ship.

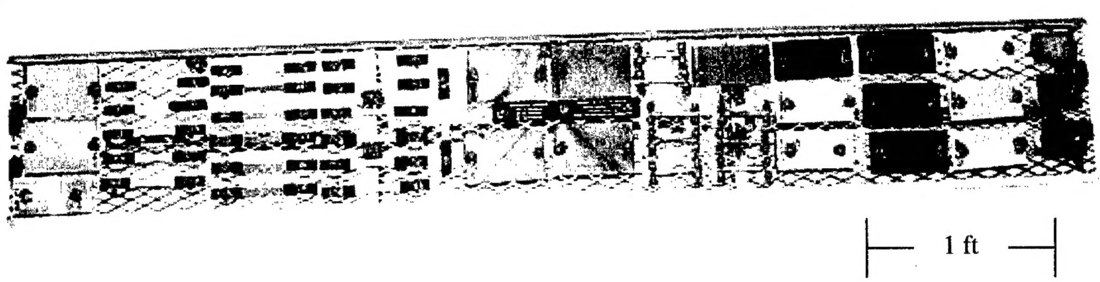

Figure 1: Shipboard Exposure Corrosion Test Rack

COMPARISON OF ADHESIVE BONDING PRIMERS FOR ALUMINUM

In support of qualification of environmentally-friendly adhesive bonding primers for aluminum, 2024-T3 aluminum lap shear specimens were exposed for 6 months on a diesel-powered carrier followed by 6 months on a nuclear powered carrier. The aluminum substrates were phosphoric acid anodized in accordance with ASTM D3933 [3], primed with water-borne and solvent-borne adhesive bonding primers and bonded with various commercial adhesives. After 12 months on board the carriers, specimens were removed and tested at room temperature in shear by tension loading per ASTM D1002 [3]. Results are shown in table 1. Each group represents the average of 10 specimens. The extremely low fracture strength values shown for the last four water-borne, nonchromated primers resulted because some or all of the specimens failed while on board ship. For the first three adhesive types (designated EA), fracture strengths were comparable to those of the other bonding primers shown in table 1. Thus, the most environmentally-friendly water-borne, nonchromated primer was not comparable overall to the other two primers.

Comparing specific adhesives, the strength of the water-borne, chromated primer specimens was comparable to that of the less environmentally friendly solvent-borne chromated primer specimens. This type of environmentally advantaged adhesive bonding primer is finding increased usage in commercial as well as military applications. It should be noted that toughness of the adhesive-primer combinations, as revealed by peel strength tests, was not evaluated in these tests.

Table 1: Fracture Strength of Adhesive Bonded Lap Shear Specimens (MPa)

Adhesive	Water Borne, Non-Chromated Primer	Water Borne, Chromated Primer	Solvent Borne, Chromated Primer
EA934NA	19.7	22.0	17.8
EA9628	40.7	40.4	36.4
EA9689	21.9	22.0	20.9
FM73	32.4	40.4	39.0
FM94	1.0	37.9	36.5
FM300	~ ~	27.4	~ ~
FM300-2	~ ~	40.3	~ ~
FM300K	17.0	33.2	23.1
FM300-2K	15.5	~ ~	38.9
MAG6363	0.0	30.1	31.1

SHIPBOARD EXPOSURE OF ALUMINUM-LITHIUM ALLOYS

Reduction of density and increase of elastic modulus of aluminum alloys occurs with the addition of lithium, providing an opportunity to reduce the weight of aircraft structures. Among the early generation of Al-Li alloys, developed in the 1970's and 1980's, were alloys 8090 and 2090, containing between 2 and 2.5 weight percent lithium. Alloy 8090 was developed as a medium strength, damage tolerant alloy with a higher elastic modulus than 2024 aluminum and it is can be superplastically formed. Alloy 2090 is a high strength alloy with a higher elastic modulus than 7075 aluminum. Flat tensile specimens of the aluminum-lithium alloys were exposed for a total

of 12 months on board aircraft carriers, along with 7075 and 6013 aluminum alloys. 7075 aluminum specimens in the peak aged (T6) condition and overaged (T7) condition were exposed in the longitudinal (L) and transverse (T) orientations. The average percentage loss in static properties after exposure is shown in table 2. The aluminum-lithium alloys sustained the greatest losses in ductility. The superplastically formed 8090 alloy, especially, lost the most in static strength and ductility. The 7075 and 6013 alloys in the T6 condition also sustained considerable losses in ductility, which were not as great for the 7075-T7 alloy.

Table 2: Percent Reduction in Static Properties of First Generation Aluminum-Lithium Alloys

Alloy	UTS	YS	Elongation
2090-T8	11	9	89
8090-T8	21	12	87
8090 SPF	53	43	99
7075-T6 (L)	6	3	78
7075-T6 (T)	7	5	87
7075-T7 (L)	3	4	51
7075-T7 (T)	6	5	45
6013-T6	13	13	76

The next generation of aluminum-lithium alloys was developed in the late 1980's and 1990's. These alloys contain less than 2 weight percent lithium, with correspondingly less weight savings. An experimental alloy, X2096, now commercially designated 2196, is a high strength, high toughness alloy with one of the lowest densities among the second generation alloys. Experimental alloy RX818, now commercially designated 2098, is a high strength, high fracture toughness alloy, designed for thin gage aircraft skins. Alloy 2195 is also a high strength alloy with reportedly good postweld properties. Alloy 2297 was developed for thick plate applications, such as aircraft bulkheads, with reported fatigue crack growth rates comparable to 7050 aluminum and with greater thermal stability than other 2000 series aluminum alloys. The second generation aluminum-lithium alloys, along with 7050-T7, were subsequently exposed for a total of 12 months on aircraft carriers at sea. The average percentage loss for these alloys after exposure is shown in table 3. Of the four aluminum-lithium alloys exposed, alloy 2297-T8 sustained the least reduction in ductility, similar to that of 7050-T7. Among these alloys, 2297-T8 appears to be most favorable for plate applications with regard to real time exposure to the severe carrier environment. Absolute static properties after exposure were 418MPa (60.7ksi) ultimate tensile strength, 384MPa (55.7ksi) yield strength and 9.6% elongation.

Table 3: Percent Reduction in Static Properties of Second Generation Aluminum-Lithium Alloys			
Alloy	UTS	YS	Elongation
X2096-T8	9.8	9.0	41.0
RX818-T8	4.5	5.0	22.0
2195-T8	8.7	8.6	25.0
2297-T8	6.2	6.2	14.0
7050-T7	8.0	8.0	18.0

LABORATORY ACCELERATED TESTS AND SHIPBOARD EXPOSURE OF AIRCRAFT ALUMINUM ALLOYS

The static tensile properties of three aluminum alloys in laboratory Sulfur Dioxide (SO_2)/salt spray chambers were evaluated in comparison to shipboard exposure.

Alloy 7075 is a high strength wrought product often used for highly stressed structural parts in the peak aged T6 temper. In this condition, however, it has its lowest toughness and resistance to stress corrosion cracking. Aluminum alloy 2024 is also a heat treatable wrought product with high toughness and ductility, which has commonly been used in naval aircraft for over 50 years.

Alloy 7249-T76 is a relatively newer alloy produced in wide and narrow extrusions, utilizing a nonproprietary two-step aging procedure with strength comparable to 7075-T6 and with superior resistance to corrosion. This alloy was investigated and later selected by Lockheed Martin as one of the two alloys to replace 7075-T6 wing panels of P-3 aircraft as part of the Service Life Assessment Program, September 2001 [4]. The chemical compositions of the three alloys are presented in table 4.

Table 4: Composition of Shipboard Exposed Aluminum Alloys

Material	Element (Weight Percent)								
	Al	Cr	Cu	Fe	Mg	Mn	Si	Ti	Zn
7249-T76	Bal.	0.12-0.18	1.3-1.9	0.12	2.0-2.4	0.1	0.1	0.06	7.5-8.2
2024-T3	Bal.	0.1	3.8-4.9	0.5	1.2-1.8	0.9-0.9	0.5	0.15	0.25
7075-T6	Bal.	0.18-0.28	1.2-2.0	0.5	2.1-2.9	0.3	0.4	0.2	6.1

In order to ensure the uniformity of the surface condition, all specimens prepared for mechanical testing were etched in 5% Sodium Hydroxide (NaOH) solution, cleaned in Nitric Acid (HNO_3), rinsed in deionized water and air-dried. Flat tensile specimens of each alloy were machined and tested to determine the static mechanical properties: ultimate tensile strength (UTS), yield strength (YS) and percent elongation. Three specimens of each alloy were tested unexposed as controls, forming the baseline data values.

Six test specimens prepared and machined to the same tolerance were subjected to exposure aboard aircraft carriers. The static tensile properties of the three alloys: 7075-T6, 2024-T3, and

7249-T76 after shipboard exposure are presented in figure 2, with the unexposed properties shown above each bar. The results in this figure are average measurements of exposed test specimens, conducted according to ASTM standard E8 [3] performed on a closed-loop servo hydraulic MTS machine with a crosshead speed of 0.05 in./min. Although two deployments totaling 12 months were planned for the shipboard exposure, the second deployment was extended due to exigencies of the Navy and so a total of sixteen months exposure was experienced. Figure 2 shows that ductility was greatly reduced after shipboard exposure, especially for 7075-T6.

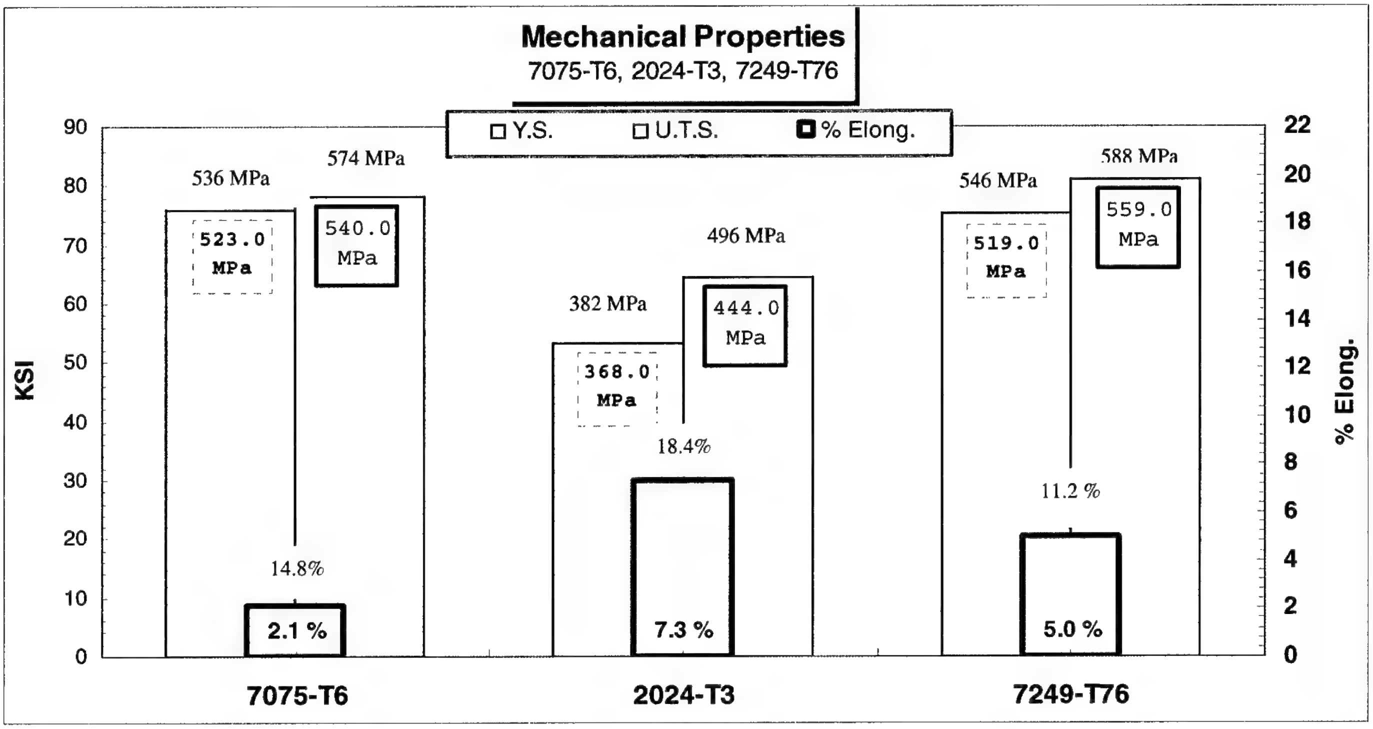

Figure 2: Static Tensile Properties of Carrier Exposed Aluminum Alloys

A clearer representation of the degradation of static properties is shown by normalizing the results against the properties of the alloys prior to exposure, as seen in figure 3. Relative loss for tensile and yield strengths for all three alloys were less than 10% of their baseline strengths. The greatest property loss occurred in the ductility, with 7075-T6 retaining only 14% of its original elongation value. By comparison, 2024-T3 retained 40% and 7249-T76 retained 45%. This major loss in ductility for 7075-T6 results from the peak aged condition and sensitivity to exfoliation corrosion.

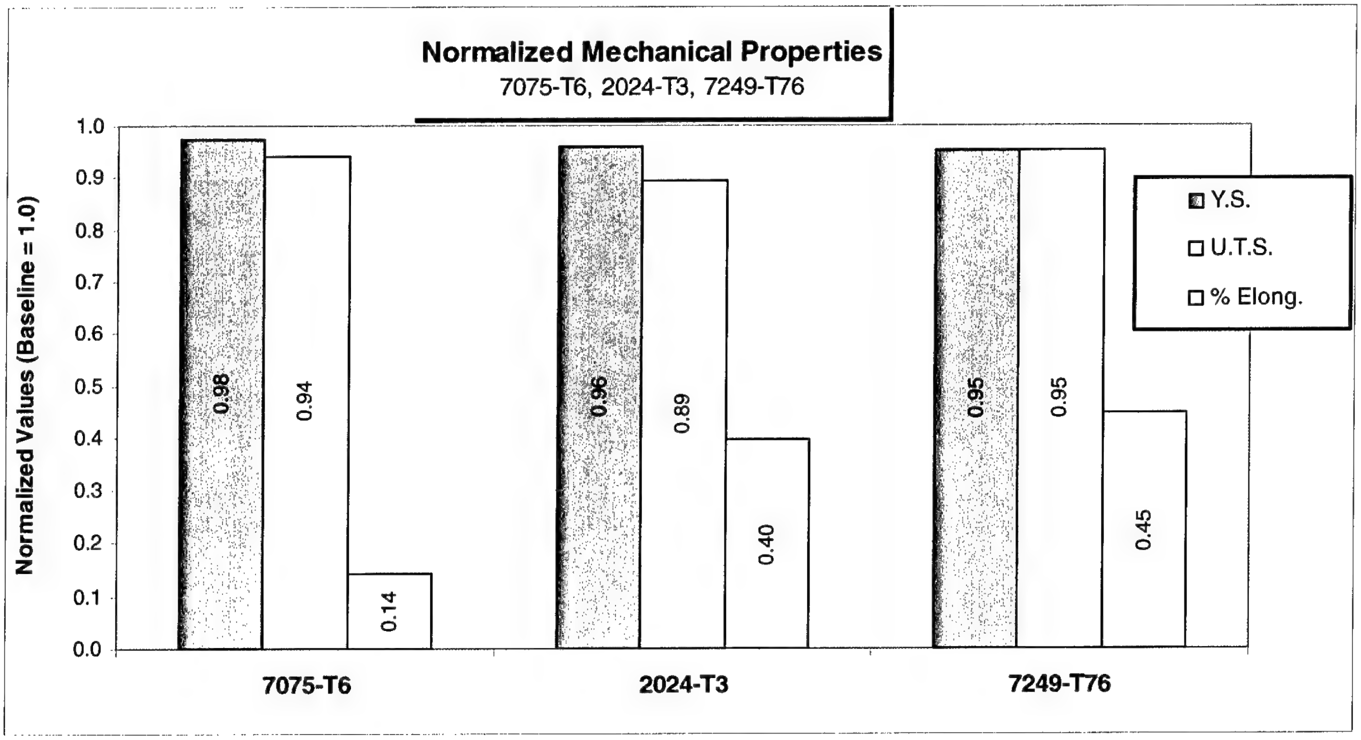

Figure 3: Normalized UTS, YS, and Percent Elongation

A cross section of a 7075-T6 panel exposed along with the tensile specimens is shown in figure 4. This panel demonstrates the delamination effect of exfoliation corrosion in a shipboard occurring during shipboard exposure, which is not always reproduced in laboratory accelerated tests. Based on retention of mechanical properties, 7249-T76 was best suited to the shipboard environment.

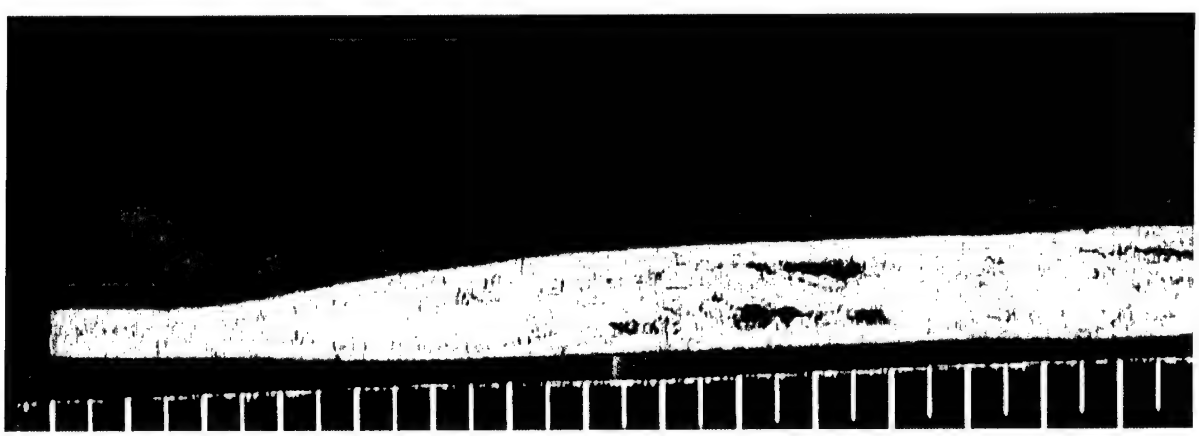

Figure 4: Exfoliation of 7075-T6 Panel after Shipboard Exposure

Earlier studies performed on these alloys and other naval aircraft materials have clearly demonstrated the severe sea environment in which naval aircraft materials are exposed.

The difficulties in conducting valid laboratory accelerated tests have been described [5]. Although shipboard tests provide indications of the corrosion behavior of the alloys used in Naval aircraft, it is important to note that the environment of an aircraft carrier at sea changes from one deployment to another depending on the time of year and the area of operations. Simulation of the most severe conditions by means of cyclic SO_2/salt spray testing provides insight into the behavior of materials used in Navy aircraft, for comparison to actual exposure at sea.

Fifteen test specimens of each of the 3 alloys were tested in a laboratory environment involving an SO_2 salt spray chamber designed in accordance to ASTM G85 [3]. Three specimens from each alloy were removed from the test chamber for mechanical testing after 50, 100, 200, 300, and 500 hr of exposure. Figures 5, 6 and 7 present the UTS, YS, and percent elongation of the three alloys compared to the shipboard exposure values. The shipboard exposure test results are boxed and marked to the far right side of each figure.

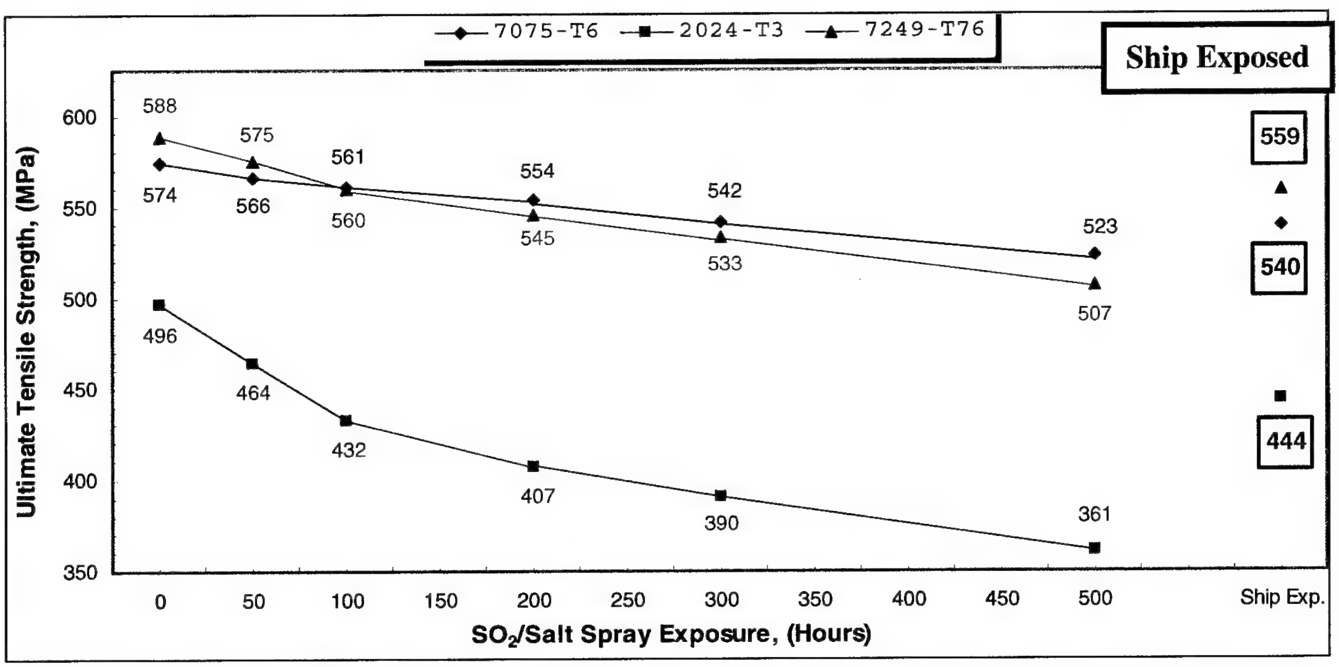

Figure 5: UTS Accelerated Laboratory Tests and Shipboard Exposure Comparison

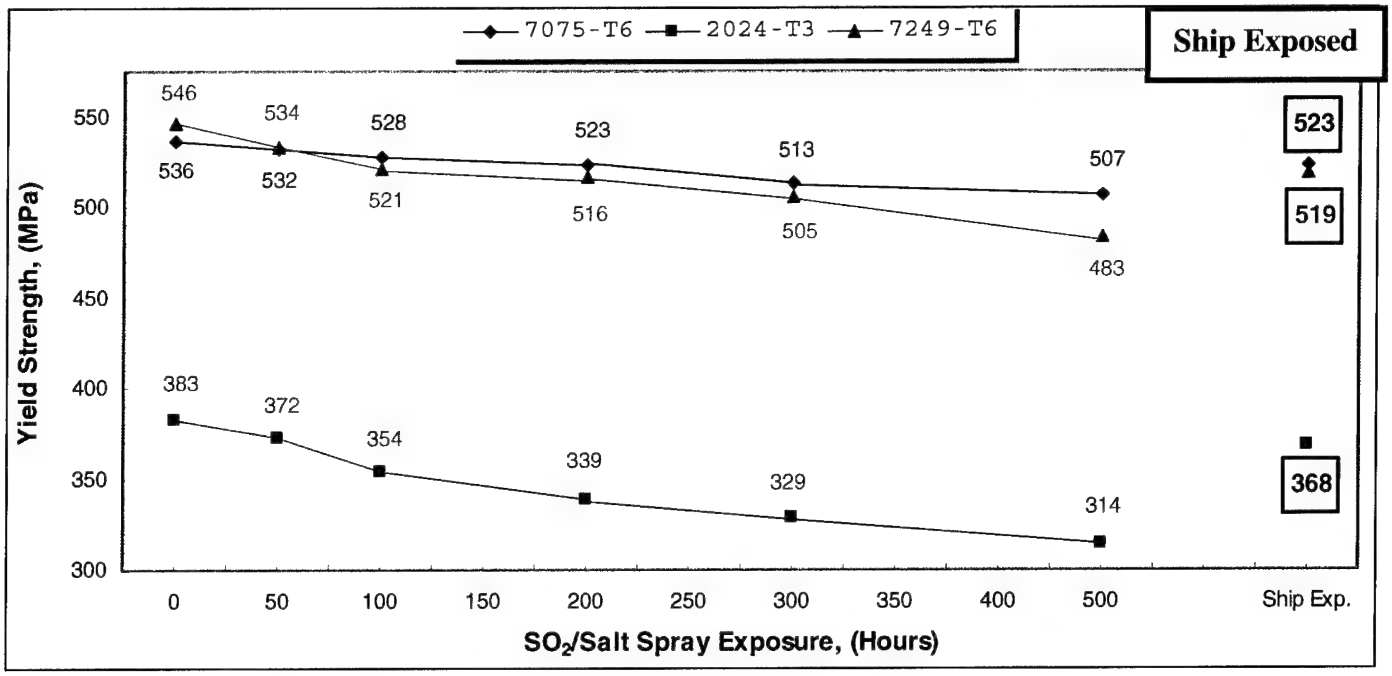

Figure 6: YS Accelerated Laboratory Tests and Shipboard Exposure Comparison

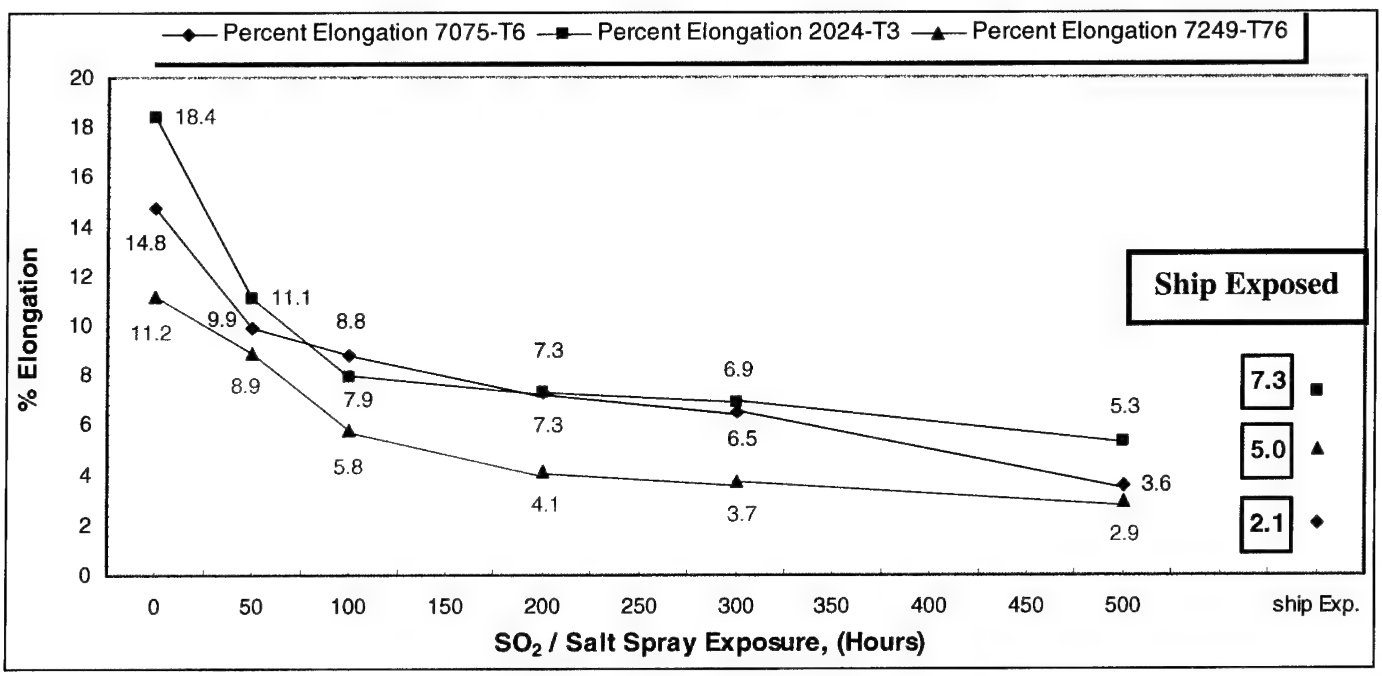

Figure 7: Ductility Accelerated Laboratory Tests and Shipboard Exposure Comparison

Table 5 represents a comparison of the corresponding time in hours between the shipboard exposed specimens and the laboratory accelerated tests as evaluated for static tensile properties and ductility.

Table 5: Equivalent Time Comparison of Shipboard Exposure and Laboratory Accelerated Tests (Hours)

S.B.E. (Material)	U.T.S. (Hours)	Y.S. (Hours)	% Elong. (Hours)
7075-T6	310	200	>500
2024-T3	80	60	200
7249-T76	100	140	140

It can be seen that the degradation of static properties after 16 months exposure on two carrier deployments compared to a wide range of 80 to 310 hr of accelerated laboratory testing with regard to UTS (figure 5 and table 5) and 60 to 200 hr with regard to YS (figure 6 and table 5). The loss in ductility for the 2024 and 7249 alloys compared to approximately 200 and 140 hr of laboratory testing, respectively (figure 7 and table5). The severe loss in ductility for 7075-T6 (also shown in table 2 for other deployments) did not occur in laboratory testing up to 500 hr (figure 7 and table 5). Note the static tensile properties and ductility results of shipboard testing for the 7249 compared to a narrower range of 100 to 140 hr of accelerated laboratory testing. It is apparent that the shipboard exposure testing provides critical real time data on the behavior of aircraft alloys in a severely corrosive environment, which is not reproduced consistently in laboratory testing. The rates of corrosive attack are not duplicated in laboratory testing for various materials and, therefore, the real time exposure of aircraft materials at sea is necessary to provide a clear understanding of their ultimate behavior. It is considered likely that other commercial and military aircraft materials exposed to maritime or seacoast environments could eventually sustain similar degradation of properties over longer periods of time.

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CONCLUSIONS

Individual alloy correlations were obtained between laboratory accelerated tests and results seen after shipboard exposure.

Carrier exposure during deployment provides real time data characterization of the behavior of aircraft materials.

Environmentally friendly, water-borne nonchromated adhesive bonding primers for aluminum do not compare favorably with either water-borne or solvent-borne chromated primers with regard to fracture strength. Water-borne chromated primers compared favorably to the least environmentally friendly solvent-borne chromated primers for all tested adhesives.

Superplastically formed aluminum-lithium alloy 8090 sustained severe losses in ductility, while a newer generation alloy 2297-T8, had good retention of static properties during carrier exposure.

Aluminum alloy 7075-T6, which has a known susceptibility to exfoliation corrosion, also demonstrated severe losses in ductility during exposure. By comparison, alloy 7249-T76 retained its static properties to a greater extent.

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